Virtual Diagnostic Interface: Aerospace Experimentation In The Synthetic Environment

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Abstract. The Virtual Diagnostics Interface (ViDI) methodology combines two-dimensional image processing and three-dimensional computer modeling to provide comprehensive *in-situ* visualizations commonly utilized for in-depth planning of wind tunnel and flight testing, real time data visualization of experimental data, and unique merging of experimental and computational data sets in both real-time and post-test analysis. The preparation of such visualizations encompasses the realm of interactive three-dimensional environments, traditional and state of the art image processing techniques, database management and development of toolsets with user friendly graphical user interfaces. ViDI has been under development at the NASA Langley Research Center for over 15 years, and has a long track record of providing unique and insightful solutions to a wide variety of experimental testing techniques and validation of computational simulations. This report will address the various aspects of ViDI and how it has been applied to test programs as varied as NASCAR race car testing in NASA wind tunnels to real-time operations concerning Space Shuttle aerodynamic flight testing. In addition, future trends and applications will be outlined in the paper.

INTRODUCTION

The advent of affordable very high powered desktop computer processing has provided a level of access to advanced three-dimensional computer graphics that have never before been available outside of a limited, computer science orientated environment. Today's personal computer (PC) based systems with workstation class graphics cards are capable of displaying and manipulating highly complex three-dimensional geometries with detailed texture maps under stunning simulated lighting conditions. The origins of these capabilities began to emerge in the early 1990's, and were immediately put to use in support of advanced wind tunnel and flight test instrumentation systems being developed at the NASA Langley Research Center (LaRC). This paper will review the applications of three-dimensional modeling and simulation work developed in the Advanced Sensing and Optical Measurement Branch (ASOMB) over the last seventeen years, concentrating on the current suite of applications and our plans for future development.

What is ViDI?

The Virtual Diagnostics Interface, or ViDI, is a methodology of applying two-dimensional image processing, three-dimensional computer graphics, physics-based modeling, and the handling of large data sets to use in solving complex aerospace testing and data visualization problems. To date, most of the two-dimensional image processing has been developed within NASA, while the three-dimensional visualization capabilities have been derived from Commercial-Off-the-Shelf (COTS) software packages. However, these COTS programs were chosen for their ability to be programmed and work seamlessly with custom user interfaces and libraries of physics based simulation software. There are three main areas in which ViDI is utilized: (a) pre-test planning, which involved the simulation of an experiment and the planned instrumentation system in a three-dimensional virtual world as shown in Figure 1, (b) real-time data visualization in an interactive virtual environment, and (c) post-test data unification, where disparate forms of data are brought together *in-situ* in the virtual environment to help obtain a more global perspective on the causes and relationships of experimental parameters and the resulting physical phenomena reported by the data [1].

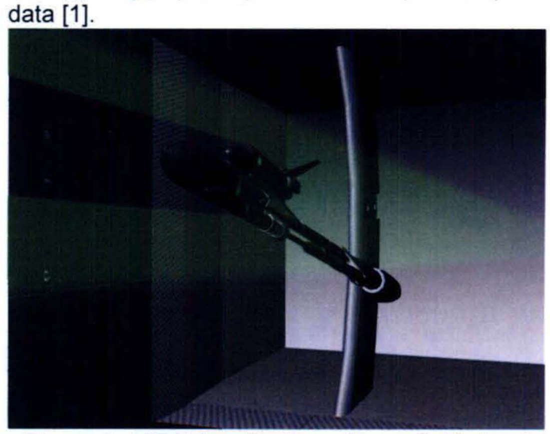


Figure 1: ViDI Visualization of laser light sheet for aerodynamic flow investigation on Space Shuttle wind tunnel model

History of ViDI

In 1990 NASA embarked upon the development of an instrumentation system to be placed aboard a flight test aircraft which would use lasers and cameras to obtain quantitative images of the velocity of the airflow of the aircraft. This instrumentation would record megabytes of data in a few seconds of operation, which at the time was problematic on several fronts. One of the first issues was how to display the time variant data images in a meaningful way. Fortuitously, the first three-dimensional computer visualization systems were coming on the market, and a DOS based commercial program, running on an Intel 486 class computer was utilized to experiment with mapping the data images into the virtual environment, Figure 2.

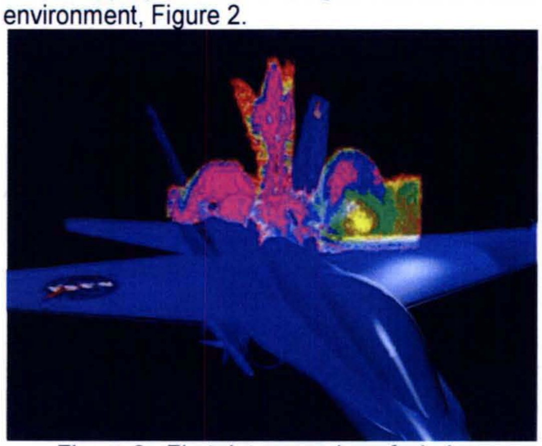


Figure 2: First data mapping of wind tunnel data representing airflow velocity over F/A-18 aircraft in preparation for flight tests of this configuration.

Almost immediately it became apparent that the camera simulation capabilities of the virtual environment would be ideal for use simulating the experiment as a whole for planning purposes. Ultimately, the instrumentation flight test series was cancelled by NASA due to funding issues, and the continued instrument development was focused on wind tunnel applications. The visualization work, then called Virtual Facilities, continued to grow, supporting a wide variety of ground based aerospace testing techniques, as well as flight test applications. Reincarnated as the Virtual Diagnostics Interface (ViDI) in the late 1990's, the scope of applications has expanded to include real-time data visualization and comparison in virtual environments, new ways of merging experimental and computational data, and support for hypersonic aerodynamic flight testing on the Space Shuttle.

CURRENT APPLICATIONS

Pre-test Planning

The cost of experimental aerospace testing is a key driver determining the design cycle of a new configuration. Modern computational techniques have relieved some of the requirements for experimental testing, but there is still a strong need to validate computational results and run tests on conditions where computational methods are not yet fully developed. ViDI has played a key role in optimizing the design of wind tunnel tests to minimize the test set-up time and ensure the desired data can be acquired.

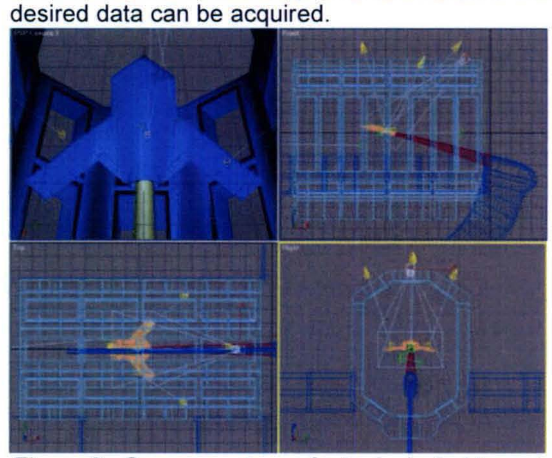
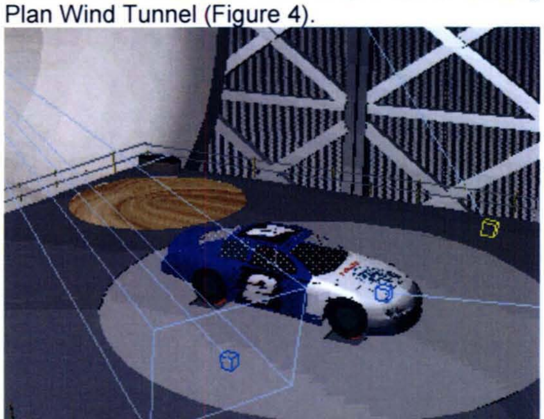


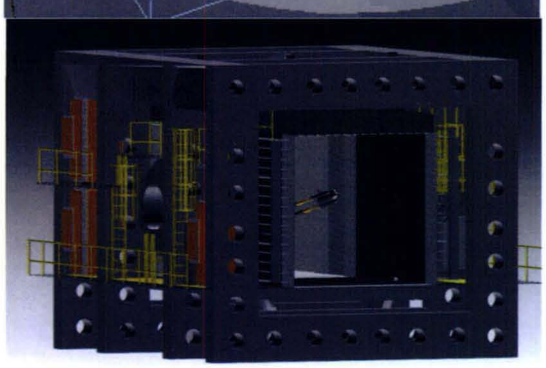
Figure 3. Screen capture of a typical wind tunnel test setup, shown here for PSP. Yellow cones represent lights; the upper left image is the simulated camera image.

ViDI utilizes the virtual world as a stage upon which an experiment can be designed. At the core of the visualization is a carefully scaled model of the test facility, usually a wind tunnel in this case (Figure 3). The model is crafted to represent both the inside and the exterior of the facility. Sufficient detail is required to provide the researcher with enough information to determine where to place items such as sensors or cameras and lights. Additionally, the researcher has to have an accurate three-dimensional computer model of the article being tested, such as an aircraft or rocket. Most often, these geometry files are provided by the company that creates the actual wind tunnel model, and are received in common Computer Aided Design (CAD) file formats. If necessary, these files can be translated into formats readable by the visualization software using commercial software products. The test configuration model files are merged with and scaled to the geometry of the experimental facility. Lastly, the mounting device, known as a sting, is added. This unites the test configuration to the facility model, and often requires dynamic modeling to provide the proper motion of the test configuration as it is pitched, rolled, yawed and translated through the test section.

Given a virtual scene that realistically mimics a planned test; the research may concentrate on how the test will be instrumented. Many advanced wind tunnel techniques utilize cameras as their sensors. Examples include Pressure and Temperature Sensitive Paints (PSP and TSP), which require specific camera views and lighting conditions on the test configuration. Additionally, Particle Image Velocimetry (PIV) measures air flow velocities using high resolution images of smoke particles in a flow, and Projection Moiré Interferometry (PMI) uses cameras and special lighting techniques to measure surface deflections. The common element is the use of cameras and lighting as integral components of the instrumentation. Using the virtual environment the researcher may experiment with camera placement, required field of view and depth of field. Multiple lighting conditions can be analyzed to eliminate unwanted shadowing, and most importantly the optical access to key regions of the flowfield can be assessed under all possible model positions and orientations. This *in-situ* investigation of experimental setups has proven to save significant time in both the test setup and the running of the experiment by eliminating surprises and providing a clear line of communications to the test team.

The examples below depict test setups for applications as varied as PSP testing in the Langley 30 x 60 Foot Full Scale tunnel on an actual NASCAR racing car to a Laser Velocimetry experiment on the Space Shuttle in the USAF Arnold Engineering Design Center (AEDC) to a NASA Ares rocket in the NASA LaRC Unitary Plan Wind Tunnel (Figure 4).





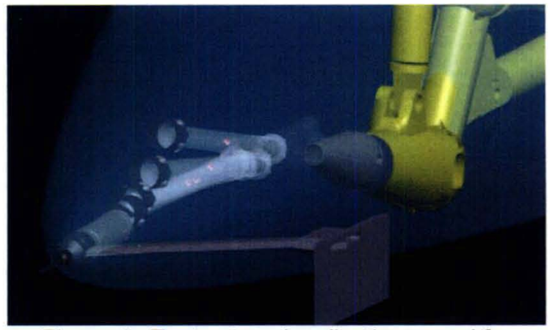


Figure 4. Test setup visualizations used for NASCAR testing, Space Shuttle flow visualization and Ares rocket stage separation testing.

Real Time Data Visualization

The virtual environment developed in the pre-test phase described above can also be used as the foundation for displaying data in real time in an interactive three-dimensional visualization. To date, three forms of data have been incorporated into the visualization; two dimensional imagery, vector forces, and scalar point information, such as pressure and temperature [2].

At the heart of the real-time data visualization is a custom program developed to feed information into the virtual environment. The first version of this software was designed to interface with cameras to provide real-time streaming video that was embedded into the virtual environment. This was especially useful for techniques such as laser light sheet flow visualization (Figure 5) or Schlieren, which provided a view of the flow that could be rapidly mapped to a plane in the virtual environment.

Following the successful deployment of the real time imagery in the wind tunnel, the system was expanded to interact with the wind tunnel Data Acquisition System (DAS). The DAS is a computer that can process hundreds of scalar parameters defining the wind tunnel environment and test conditions at a given moment in time. This provided a source of information for the three-dimensional virtual environment for pressure, temperature, tunnel velocity, forces and more. Using this information, a comprehensive visualization depicting the actual state of the experimental test article in real time was developed. Pressures and temperatures were shown as bars located at the points where the

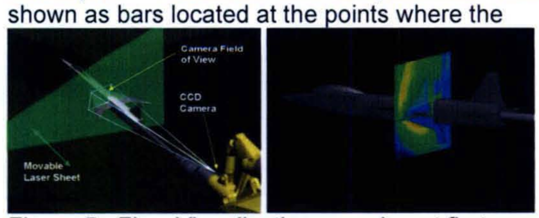


Figure 5. Flow Visualization experiment first used for real-time data visualization in the virtual environment.

sensors were located, arrows of changing magnitude represented forces and moments (Figure 6), and state information such as velocity, angle of attack, or flow temperature was affixed to the display.

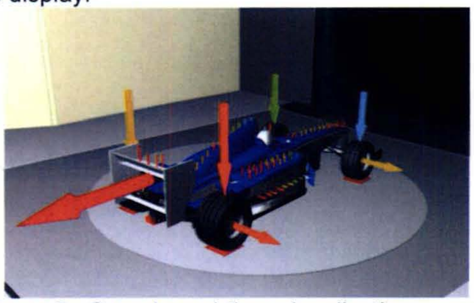


Figure 6. Sample real-time visualization – small bars on model represent measured pressures, arrows show measured forces.

An addition and very important portion of the real-time data visualization capability was the inclusion of pre-computed results from predictive methods such as Computational Fluid Dynamics (CFD). A database of computational results was stored on the ViDI computer in a manner that allows the information to be retrieved based on key test parameters, such as model attitude (roll, pitch and yaw), flow velocity or Mach number, and other pertinent parameters. Then, as the ViDI computer received data from the DAS it automatically retrieved the correct computational solution and displayed it in real time along with the experimental data. It also did a real-time differencing, which rapidly showed the level of agreement between experimental values and prediction (Figure 7). This system was run automatically for hours on end during tests, which allowed the user to concentrate on the data visualization and not the care and feeding of the software.

The real-time software has been developed with wind tunnel testing as the primary application. However, the technology is clearly not limited to just wind tunnel experiments and validation of CFD predictions. This capability can easily be expanded to include computational predictions for any form of analysis – structural, thermal, or other, and the experimental data source may originate from any form of experimental apparatus. The ViDI capability is designed to rapidly allow the user to investigate the fidelity of both the computational and experimental results, and provide a validation capability in real-time that will allow the user to identify issues during a test, while there is still time to affect the way the experiment is being conducted.

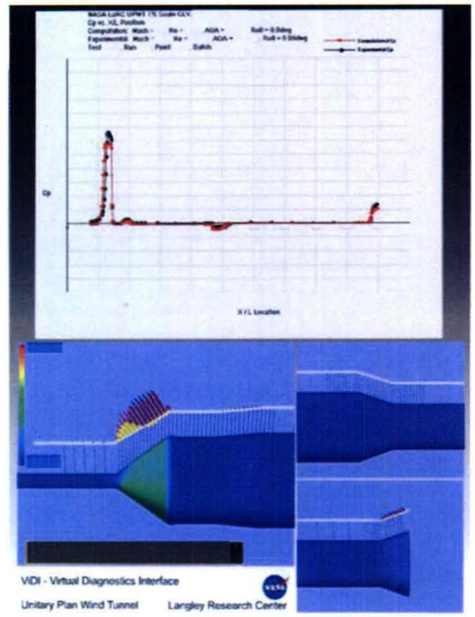


Figure 7. Display from real time test – black bars are experimental pressures, red bars are CFD pressures, surface coloration is CFD pressure distribution, yellow bars show difference from experiment and CFD. X-Y plot is also created in real time to augment visualizations.

Post–test Data Unification

Over the many decades of wind tunnel testing, data visualization has usually been confined to two-dimensional data plots. With the emergence of CFD data visualization, visualizing data sets of flow features and the physical conditions on an aerodynamic surface (pressure, temperature, shear stress, etc) became integrated with the three-dimensional representations of the test geometries. ViDI has expanded upon this to include disparate forms of experimental data unified into a single visualization, often combined with computational predictions as well. This provides two very important capabilities; the ability to compare very large quantities of experimental and computational results quickly and intuitively, and the ability to obtain a global awareness of the cause and effect relationships between the physical features and trends occurring in the datasets. This level of integration has led to better understanding of the fundamental physics, as well as the often overlooked limitations of either experimental or computational methods. Ultimately, it allows the researcher to have a far superior situational awareness of the experiment that has been conducted than is possible only with a series of traditional X-Y plots (Figure 8).

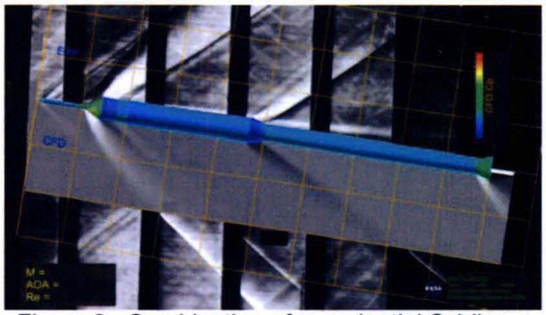


Figure 8. Combination of experiential Schlieren photograph with computational prediction of flow density as well as surface pressure distribution on Ares rocket.

Finally, ViDI has been used as a forensic tool. In instances where experimental results or computational data seem inconsistent, ViDI has allowed researchers to re-create plausible scenarios and experiment with different hypothesis to see if a scenario is physically possible and if the discrete data sources support the hypothesis.

HYTHIRM

One expansion of ViDI applications to flight testing involves the HYTHIRM (Hypersonic Thermodynamic Infrared Measurements) project. The HYTHIRM project is tasked with obtaining high resolution infrared imagery of hypersonic vehicles (flying greater than Mach 5) in flight to determine the heating on the vehicle. This is especially critical for reentry spacecraft, whose properly designed heat shields are essential to ensure adequate vehicle performance while ensuring the craft will not burn up due to inadequate protection. To date, the largest and most complex hypersonic vehicle is the Space Shuttle. After more than twenty years and one-hundred twenty flights there are still a number of important engineering questions concerning the fundamental flow physics involved in the aerodynamic behavior of the Space Shuttle during reentry [3].

The HYTHIRM project relies upon aircraft and ground based systems to locate the Space Shuttle during reentry. The vehicle is flying at velocities over Mach 18 (roughly 14,000 miles per hour) many hundreds of miles away. These imaging assets have to track the vehicle optically from close to horizon break to beyond the point of closest approach, which is typically about 30 nautical miles from the deployed infrared camera. For such a mission pre-planning is critical. Reentry trajectories are obtained from the Flight Dynamics Office (FDO) at the Johnson Space Center (JSC). These trajectories are placed in a custom ViDI program tied in with the COTS graphical software to plot the trajectory on a virtual three-dimensional Earth (Figure 9). In addition, a Space Shuttle model is animated along the trajectory, and the program allows the user to specify an imaging assets (such as a particular telescope mount on an aircraft) and quickly determine the view of the shuttle from the telescope, based on the aircraft position and the point on the Shuttle trajectory being observed (Figure 10).

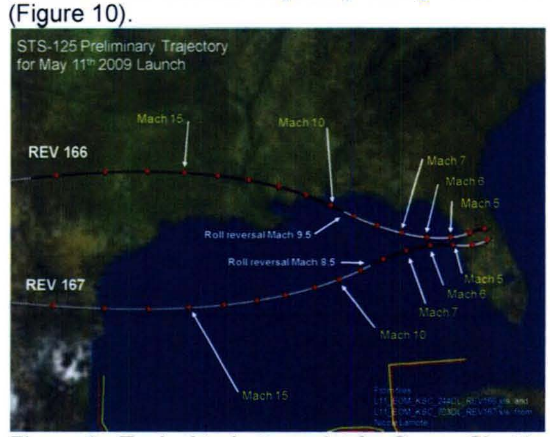


Figure 9. Typical trajectory plot for Space Shuttle reentry, shown here for the STS-125 mission.

The Space Shuttle reentry trajectories have a multitude of variables that can allow the vehicle to approach the Kennedy Space Center (KSC) by flying approaches ranging from the east of Cuba to the center of Mexico. An advanced understanding of how to position the imaging assets is a complex and essential task to ensure mission success. Additionally, it may be only hours before reentry that the actual path is known, and less than an hour before touchdown before a highly accurate track is computed. Real time updates are processed using the ViDI tools in the Mission Control Center in Houston and radioed up to the flight crews or land based telescope operators. To date, ViDI support has been provided to the two HYTIRM missions, STS-119 and STS-125, both of which had complete success in acquiring and tracking the Space Shuttle from an airborne platform, and obtaining high resolution thermal imagery of the critical underside heat shield of the Space Shuttle during descent (Figure 11).

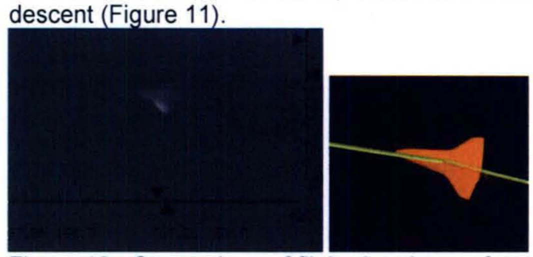


Figure 10. Comparison of flight data image from STS-119 (left) and ViDI virtual prediction prior to reentry (left).

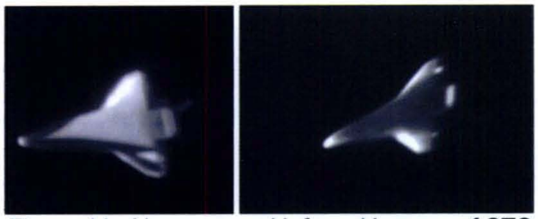


Figure 11. Unprocessed infrared images of STS-119 (left) and STS-125 (right).

Following the data capture, ViDI has been used for mapping the two-dimensional thermal images of the surface of the vehicle back to a three-dimensional geometry. This texture mapping technique relies on a unique application of spatially calibrating the data using a virtual reference. In order to properly texture map the data with scientific rigor, the data must be 'de-warped" to remove optical aberrations, perspective distortion, and foreshortening of the data on the vehicle due to the angle the vehicle makes with the camera. Traditionally, photogrammetric techniques are used that required knowledge of the exact position and orientation of the camera relative to the target object, or the Space Shuttle, in this instance. However, with this virtual calibration technique, this knowledge is not required. A reference pattern of equi-spaced dots is applied to the three-dimensional geometry of the Orbiter, and then a rendering of the Orbiter is made that matched to orientation of the actual Orbiter in the data image as closely as possible (most easily done by making the three-dimensional orbiter transparent and overlaying it on the actual data image, Figure 12.) This virtual calibration rendering is then processed by an image de-warping program (custom written at LaRC) to remap the two-dimensional data to remove all distortions and create a transformed image that appears as if it was taken from a camera directly perpendicular to the underside of the vehicle, with no perspective distortion. This image can then be mapped to the three-dimensional virtual model for data visualization.

FUTURE DEVELOPMENTS

With new measurement and visualization technologies emerging and maturing, ViDI will grow and adapt to interface with the new technologies. Despite using commercially available software, the current cost is still high enough to make the sharing and distribution of ViDI results challenging. The solution lies in platform-independent stand-alone applications that the user can open and run without additional software. These applications would use existing methods utilized by three dimensional game rendering engines or web browsers to create applications that allow the user to view and manipulate the virtual environment. The next milestone for ViDI is three dimensional displays. With three dimensional presentation methods rapidly growing in use, the future of ViDI lies in three dimensional presentations. The ability to view and move through a virtual environment with the use of active or passive three dimensional techniques would only heighten the information and understanding gained by the user.

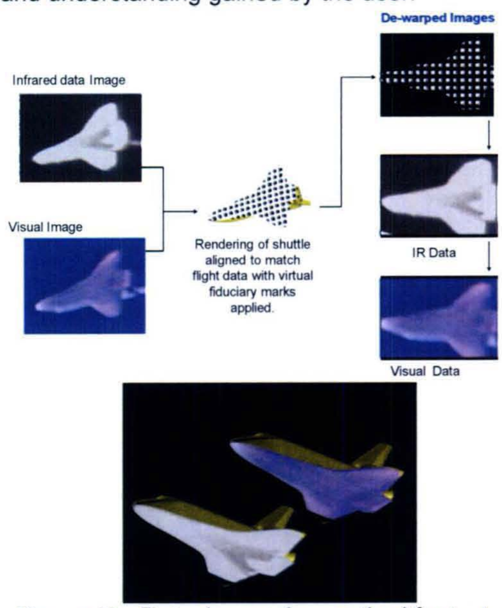


Figure 12. Data de-warping method for texture mapping thermal imagery data to Space Shuttle three-dimensional computer model.

CONCLUSION

The Virtual Diagnostic Interface software has become a powerful tool for a wide range of aerospace testing applications. The ability to rapidly combine experimental and computational data sets with three-dimensional geometry into one interactive environment gives the user a greater situational understanding throughout a test. ViDI will continue to grow its visualization capabilities in support of ground and flight test applications. As personal computing power continues to expand these techniques can still be improved upon and increased in scope. Every new project presents its own unique set of challenges to overcome and expands the capabilities of the ViDI software.

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